International Journal of Electrical and
Electronics Engineering Research (IJEEER)
ISSN(P): 2250-155X; ISSN(E): 2278-943X
Vol. 4, Issue 3, Jun 2014, 1-10

TRANS STELLAR • Journal Publications • Research Consultancy

CONSTANT ON/OFF-TIME DIGITAL PULSE WIDTH MODULATION CONTROL FOR SYNCHRONOUS BUCK CONVERTER

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ABSTRACT

This paper describes a constant on/off-time digital pulse width modulation for synchronous buck DC-DC converter to reduce the switching frequency and switching losses. Compared to constant frequency modulation, constant on-time modulation control or constant off-time modulation control can achieve fine time resolution with small circuits. However, the switching frequency increases dramatically for the constant on/off-time modulation method under heavy/light load conditions, respectively. By using this control technique, under light load condition, constant on-time modulation control is used while constant off-time modulation control is adapted under heavy load condition. It eliminates the need of high performance controller and switching frequency can be limited to a certain range. This control technique is verified through simulation and successfully implemented the control strategy in real-time by employing a dSPACE controller 1104.

KEYWORDS: DC/DC Converter, Digital Pulse Width Modulation (DPWM), Digital Signal Processing and Control Engineering (dSPACE)

INTRODUCTION

Digital controls are increasingly used in power converters because of their advantage when compared to analog controls [1]. The main advantages of using digital controls over analog are the ability to perform more advanced and sophisticated functions that potentially result in improving power conversion efficiency and/or dynamic performance of the power converter, the ease of digital control function and loop upgradeability, and reduced sensitivity to component variations compared to analog controllers [2]. However, there are still some critical challenges when applying digital control to high-frequency switched-mode power supplies. Among them, the limit cycle oscillation caused by quantization process (such as due to an A/D converter) in the feedback loop is the major problem. Reduction of the limit cycle oscillation requires high resolution DPWM. Several techniques have been proposed to increase modulation resolution, such as dithering technique [3], delay-line-based DPWM and hybrid DPWM [4] (which is a combination of counter-based structure and delay-line structure). Besides the traditional constant frequency control, Li et al. proposed voltage-mode digital constant on-time modulation method and constant off-time method, which achieve significant improvement on the resolution of DPWM. This Control technique is varied through simulation and an experimental demonstration is carried out with the rapid prototyping and real-time interface system dSPACE.

SYNCHRONOUS BUCK CONVERTER

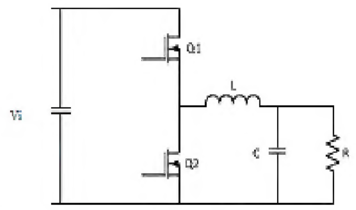

Figure 1: Synchronous Buck Converter

A typical block diagram for a step-down (buck) regulator is shown in Figure 1. The main components are Q1, which is the high-side power MOSFET; L, the power inductor; and C, the output capacitor. For a synchronous-buck topology, a low-side MOSFET (Q2) is used. In a nonsynchronous buck topology, a power diode (D) is used. In a synchronous converter, the low-side power MOSFET is integrated into the device. The main advantage of a synchronous rectifier is that the voltage drop across the low-side MOSFET can be lower than the voltage drop across the power diode of the nonsynchronous converter. If there is no change in current level, a lower voltage drop translates into less power dissipation and higher efficiency [5]. However, synchronous rectification requires non-overlap logic to avoid supply shunt currents which results when both transistors are on.

When the transistor Q1 is on and Q2 is off, the input voltage appears across the inductor and current in inductor increases linearly. In the same cycle the capacitor is charged. When the transistor Q2 is on and Q1 is off, the voltage across the inductor is reversed. However, current in the inductor cannot change instantaneously and the current starts decreasing linearly. In this cycle also the capacitor is also charged with the energy stored in the inductor. There is the possibility of two modes of operation namely continuous and discontinuous mode. In continuous mode, the inductor current never reaches zero and in discontinuous mode the inductor current reaches zero in one switching cycle. At lighter load currents the converter operates in discontinuous mode. The regulated output voltage in discontinuous mode no longer has a linear relationship with the input voltage as in continuous conduction mode operation.

The relationship among the input voltage, output voltage, and the switch duty ratio D can be derived from the inductor volt-second. For the buck converter,

$$(V_{in} - V_o)DT = -V_o(1 - D)T \tag{1}$$

$$V_o = DV_{in} \tag{2}$$

where D = $\frac{t_{on}}{T}$is the duty ratio

For the buck converter, the value of the filter inductance that determines the boundary between CCM and DCM is given by,

$$L_b = \frac{(1-D)R}{2f} \tag{3}$$

To limit the peak-to peak value of the ripple voltage below a certain value V_r, the filter capacitance C must be greater than

$$C_{min} = \frac{(1-D)V_o}{8V_r L f^2} \tag{4}$$

CONSTANT ON/OFF TIME DIGITAL PWM CONTROL TECHNIQUE

The constant on/off time PWM controller block diagram is shown in Figure 2 together with a prototype synchronous buck converter. As shown in Figure 2, output voltage feedback is used to regulate the output voltage, and output current feedback is used to determine the modulation method. In this block diagram, constant on-time modulation control and constant off-time modulationcontrol are included in the digital control unit as shown in Figure 3. When the switch is connected to "0", the converter will be operated by the constant on-time modulation controller. When the switch is connected to "1", the converter will be operated by the constant off-time modulation controller. The status of the switch, "1", or "0", is determined by output current such that the switching frequency keeps in a lower manner under any load condition. The threshold value of load current for the change of switching status will be determined by the upper bound of the switching frequency.

- If the reference voltage is greater than actual voltage, increase of duty is required. For constant on-time modulation control, the off-time should be reduced to reflect this request of duty increase. However, for constant off-time modulation control, the on-time should be increased in order to increase the duty under this circumstance.
- If the reference voltage is less than actual voltage, decrease of duty is required. For constant on-time modulation control, the off-time should be increased, for constant off-time modulation control, the on-time should be decreased in order to decrease the duty under this circumstance.

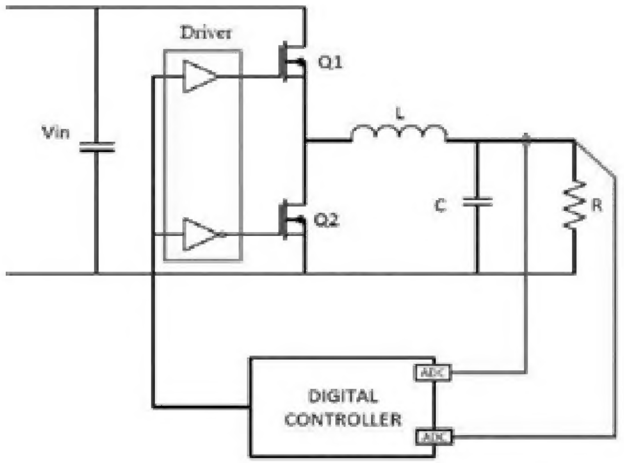

Figure 2: Buck Converter with Digital Controller

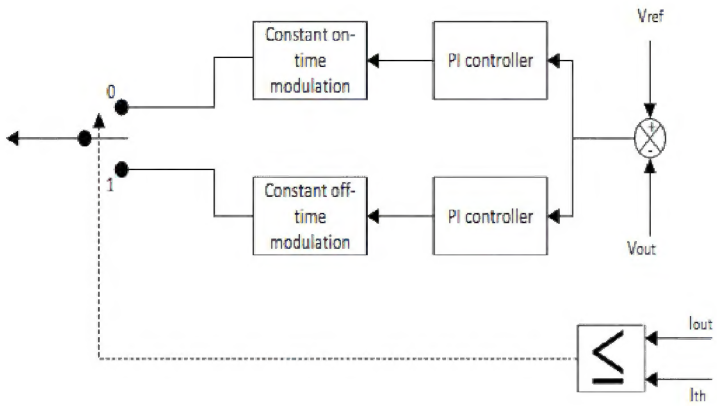

Figure 3: Block Diagram of on/off-Time Modulation Control Method

SIMULATION RESULTS

The performance of the constant on/off time modulation control has been investigated extensively at different operating conditions. Simulink model of buck converter with constant on/off time modulation control is shown in figure 4. Sample simulations results are presented below. Simulation results under both light and heavy load conditions are shown. The reference voltage is set as 6V. The threshold value of load current for the change of switching status will be determined by the upper bound of the switching frequency. The threshold value of load current is set as 0.1A. When the load current value is less than threshold value (0.1A), constant on-time modulation used as shown in figure 7 and when the load current value is higher than threshold value, constant off-time modulation used as shown in figure 8. Modulation control with step variation of voltage from 6 to 8 is shown in figure 9. From this figure it is clear that the output voltage closely follows the reference voltage, and voltage regulation is obtained. By using two parallel resistors of 100 each, constant on/off time modulation under varying load conditions can be done at 0.04sec by using a step signal as shown in figure 10. When the load current is 0.06 (less than threshold value) constant on time modulation and load current is 0.12 (greater than threshold value) constant off-time modulation control are obtained. This verify the control technique.

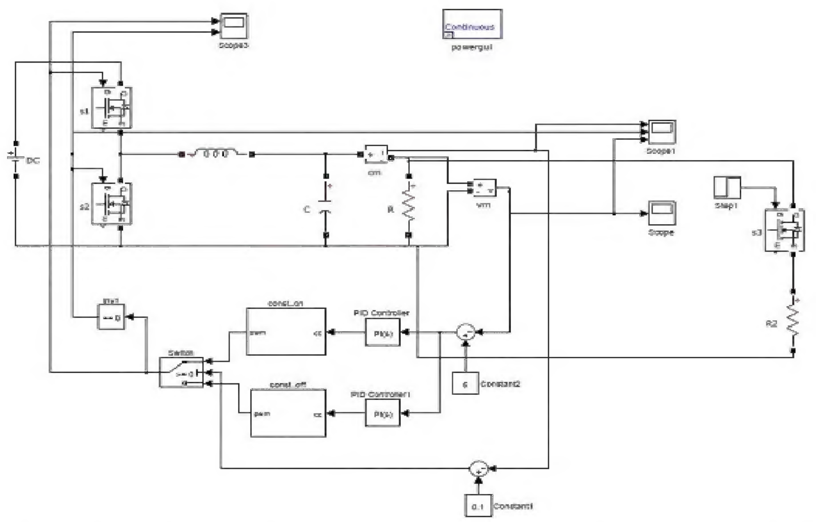

Figure 4: Simulink Model of Constant on/off Time Modulation Method

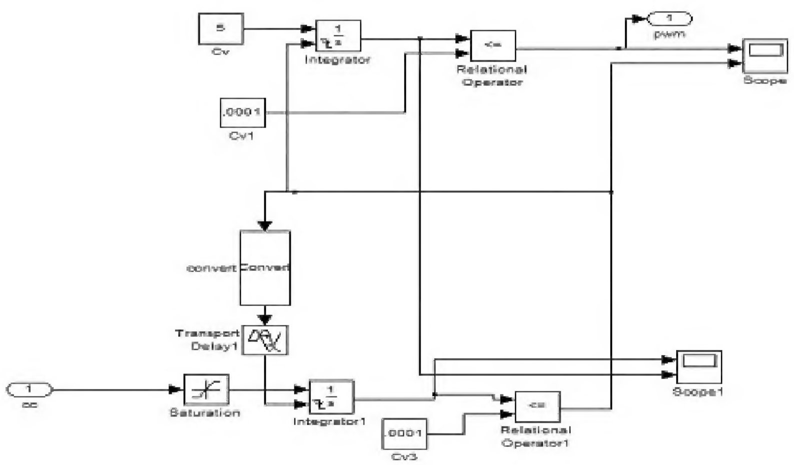

Figure 5: Constant On-Time Modulation Control

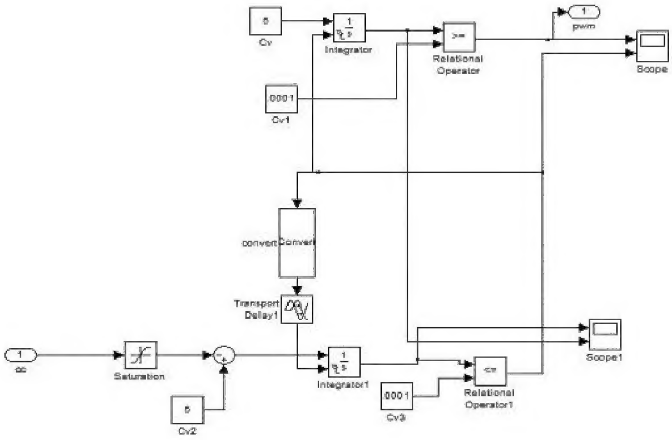

Figure 6: Constant Off -Time Modulation Control

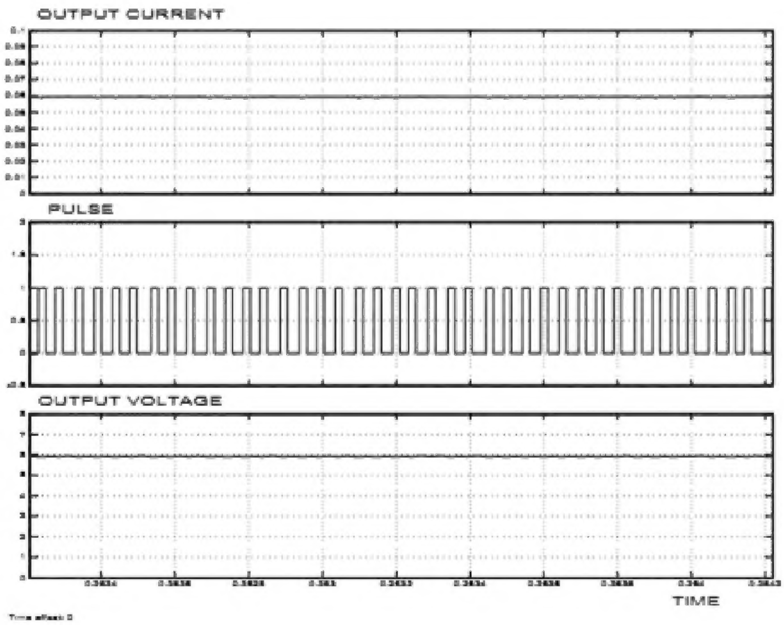

Figure 7: Constant On-Time Modulation Control

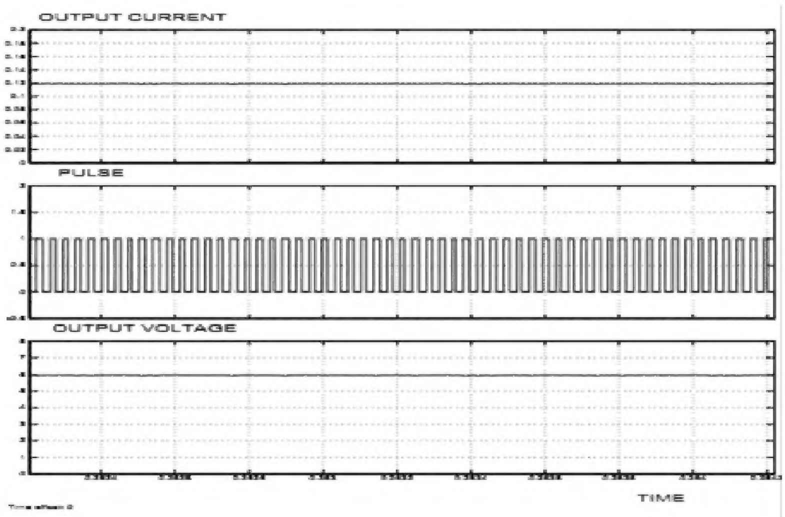

Figure 8: Constant Off-Time Modulation Control

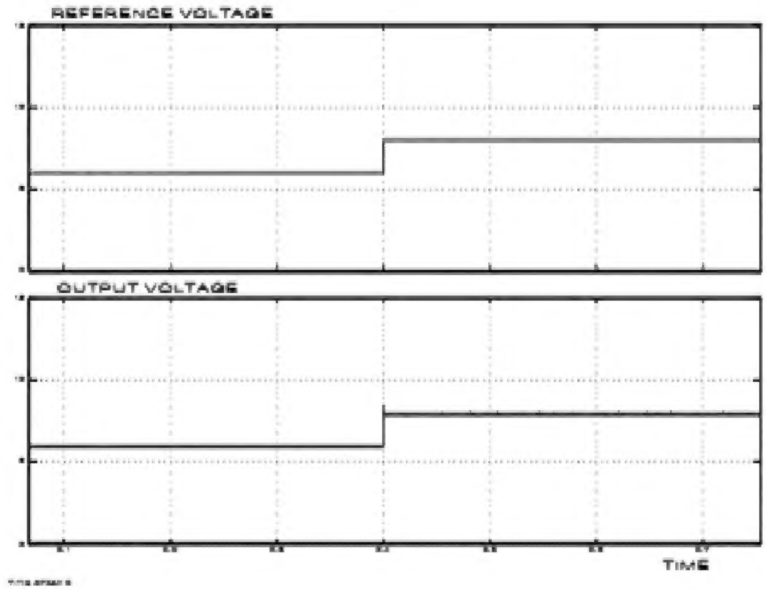

Figure 9: Modulation Control with Step Signal as Voltage Reference

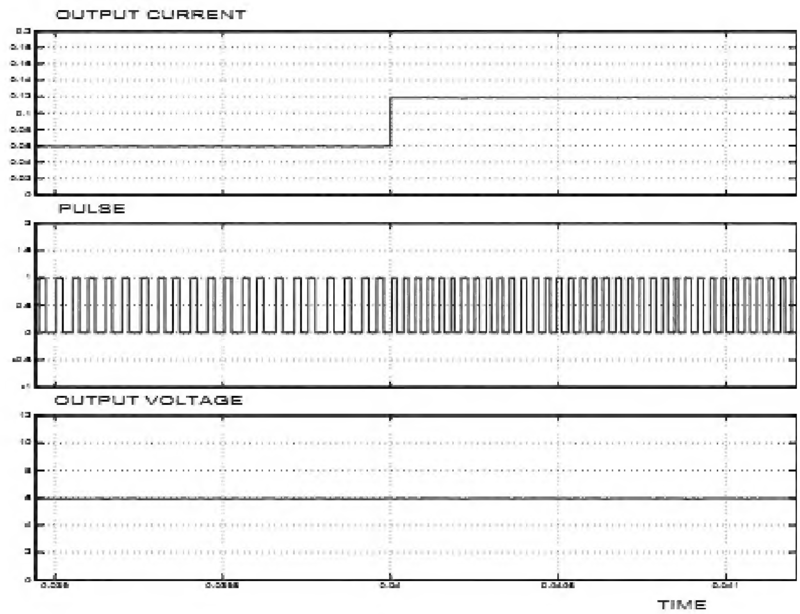

Figure 10: Constant on/off Time Modulation Control

EXPERIMENTAL IMPLEMENTATION

The control technique is experimentally implemented using dSPACE 1104 through both hardware and software. dSPACE provides tools for developing, testing and calibrating electronic control units (ECUs) in the automotive, aerospace, power electronics and medical engineering industries, as well as in industrial automation (mechatronics). Also provides the necessary hardware platform consisting of a processor and interfaces for sensors and actuators, plus the Simulink blocks needed to integrate the interfaces into the Simulink model (Real-Time Interface, RTI)

The DSP board is interfaced to PC with uninterrupted communication capabilities through dual-port memory. The digital controller was implemented with the rapid prototyping and real-time interface system dSPACE. The dSPACE can be used to control the operation of the converter via its Control Desk. Schematic of the Practical Implementation is

shown in figure 8. The DSP has been supplemented by a set of on-board peripherals used in digital control systems, such as A/D, D/A converters, and incremental encoder interfaces. The dSPACE 1104 is also equipped with a TI TMS320C240 16-bit DSP processor. DSP that acts as a slave processor and provides the necessary digital input/output (I/O) ports and powerful timer functions such as input capture, output capture, and pulse width modulation (PWM) waveform generation. In this study, the slave processor is used for digital I/O configuration. The buck converter output current and output voltage are measured and are fed to the dSPACE board through the A/D converter. Output voltage feedback is used to regulate the output voltage, and output current feedback is used to determine the modulation method. That is the status of the switch, "1" or "0" is determined by output current such that the switching frequency keeps in a lower manner under any load condition. The comparator compares the command currents with the corresponding actual currents and generates the logic signals, which act as firing pulses for the switches. Thus, PWM logic signals are the output of the dSPACE board and fed to the base drive circuit of the power MOSFETs. The D/A channels are used to capture the necessary output signals in a digital storage oscilloscope. The switching frequency range for experimental implementation of the system is 1-5 kHz. The details of the converter specifications and components are shown in Table 1. Figure 9 shows the experimental setup. dSPACE Simulink schematic and Control desk schematic are shown in Figure 10.

Table 1: Specifications

Parameters	Value
Input voltage	15V
Inductor	25Mh
Capacitor	100µF
Load resistance	100Ω
Frequency range	1KHz to 5KHz

Block diagram of the digital on/off time PWM control technique implemented using dSPACE simulink schematic and Control desk schematic are shown the figure 11. The control design phase involves developing the control algorithms that will run on an ECU, usually by modeling them graphically. This process can be performed with Simulink, modeling software from Math-works, and is outside dSPACE's application fields.

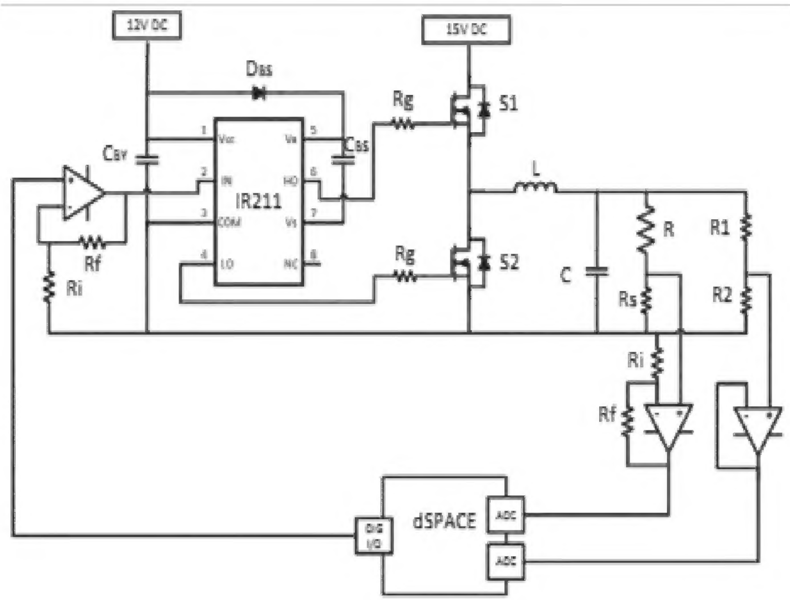

Figure 11: System of Experimental Setup

Figure 12: Experimental Setup

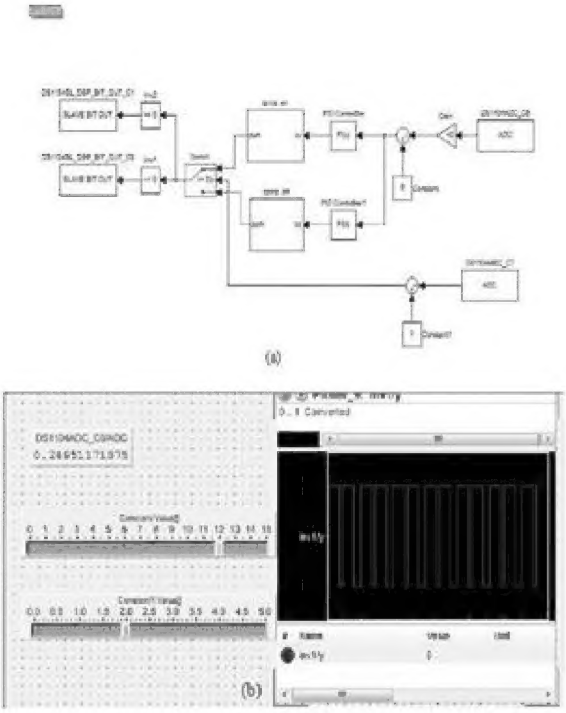

Figure 13: dSPACE Implementation (a) Simulink Schematic (b) Control Desk Schematic

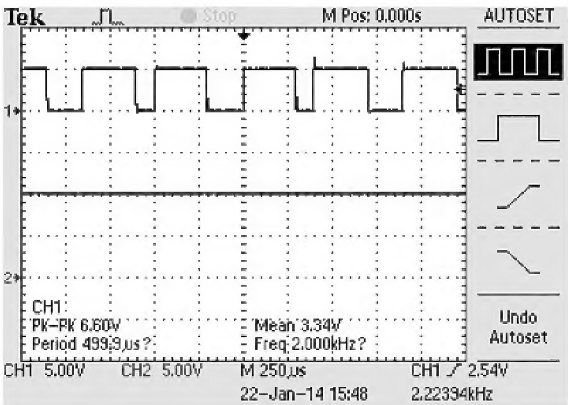

Figure 14: Experimental Results, with Reference Voltage as 10V and Current as 2A

Experimental result of constant on-time modulation under light load condition as shown in figure 6.5 with output voltage as 10V.

Difficulties faced in the hardware implementation

- Can't operate in the full duty ratio range due to frequency limitation.
- Difficulty in implementing sudden load variation. So, can't determine the proper results of on/off time modulation.

CONCLUSIONS

The paper has described a digital pulse width modulation (PWM) technique with constant on/off-time control for a synchronous buck dc/dc converter. A hardware set-up of the synchronous buck converter has been developed in the laboratory and we have also successfully implemented the digital control strategy in real-time by employing a dSPACE controller 1104. The control technique reduce the switching frequency range and switching losses, thereby increasing the efficiency.

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